

## Simulated Large Scale Propagation Test

R. Frey  
O. Lyman

U.S. Army Ballistic Research Laboratory/LABCOM  
Aberdeen Proving Ground, MD 21005-5066

D. Collis

New Mexico Institute of Technology

### INTRODUCTION

There exist in Europe, Korea, and elsewhere ammunition magazines under the control of the United States Armed Forces that cannot be utilized to their full capacity because of encroachment of public facilities within the full capacity quantity distance arc. This has led to interest in barriers which could be placed in magazines to prevent the simultaneous detonation of all of the contents. The United States Navy is also interested in barriers to prevent sympathetic detonation in the High Performance Magazine, which is now under development, and barriers between large stocks of ammunition might have other applications, such as in ports where loading and unloading operations are being conducted.

In general, such barriers are beneficial in reducing the quantity distance arc only if the quantities of ammunition are large. For Hazard Classification 1.1 materials stored in earth-covered magazines, the inhabited building distance remains constant for net explosive weights (NEW) from 1,000 to 50,000 lb. Therefore, subdivision of the stored ammunition has a major benefit only when the total NEW stored is greater than 100,000 lb.

Full-scale testing of candidate designs with this quantity of explosive is extremely expensive, costing millions of dollars per test, and is valid only for the particular type and configuration of munitions tested. Furthermore, there is considerable experience which indicates that the results of small-scale tests cannot be easily extrapolated to full scale. It appears that the mechanism of propagation of detonation can change as the scale of the test increases and as the confinement around the ammunition increases<sup>1,2</sup>. Consequently, the design of such barriers for the prevention of large-scale sympathetic detonation is not easy.

At the request of the Project Manager for Ammunition Logistics (PM AMMOLOG), we have conducted a joint experimental/computational study of how such barriers might be designed. We adopted a extremely conservative design philosophy. We assumed that the barrier must be thick enough to stop all fragments from the detonating (donor) munitions so that the protected (acceptor) munitions would not receive any direct fragment hits. Under these conditions, the biggest threat to the acceptors comes from the impact of the barrier itself. In this paper, we will describe some analysis and an experiment that was conducted to determine the effect of the barrier on the acceptor munitions. The computations are discussed in more detail in a paper by Lawrence and Starkenberg in this symposium.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>AUG 1992</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-1992 to 00-00-1992</b>	
4. TITLE AND SUBTITLE <b>Simulated Large Scale Pmpagation Test</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>U.S. Army Ballistic Research Laboratory,LABCOM,Aberdeen Proving Ground,MD,21005-5066</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>See also ADA260984, Volume I. Minutes of the Twenty-Fifth Explosives Safety Seminar Held in Anaheim, CA on 18-20 August 1992.</b>					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>12</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

## Description of the Situation To Be Simulated

For the purpose of this study, we assumed that the donor would be a stack of 155-mm or 8-inch projectiles with an NEW of 60,000 lb. Sand was chosen as the barrier material because it is cheap, readily available, and does not produce secondary fragments. Test data indicates that 380 mm of sand will stop all of the fragments from a single 8-inch round<sup>3</sup> (a composition B-loaded 155-mm round produces fragments with only slightly higher velocity and similar mass). Multiple rounds will produce fragments with higher velocity due to the interaction zones between warheads and perhaps due to other effects<sup>4</sup>. For the purpose of this study, we assumed that the barrier must be at least 500 mm thick, and preferably 1 m thick, to stop all fragments.

To determine the velocity which would be imparted to the barrier by the detonation of the donors, Lawrence and Starkenberg ran a series of calculations which are described in more detail in another paper in this symposium. To minimize computational time, the magazine was represented as a cylindrical structure, 8 m in diameter (interior), 24.4 m long (interior), with 200-mm concrete walls surrounded by 610 mm of sand (roughly speaking, this structure can be thought of as two identical magazines joined at the floor). The barrier was a cylindrical "plug," 6.8 m in diameter, in the center of the magazine. The diameter of the barrier permitted some gas flow over the "top" of the barrier. The thickness of the barrier was varied, and, on some calculations, some additional vent area was provided through the barrier. The donor charge was a solid block of TNT with a mass of 56.5 Mg (124,000 lb) (twice the mass in a single "real" magazine), and it simulated the explosive in 976 pallets of M107 rounds (488 pallets in each half of the cylindrical magazine). The storage volume of the M107 projectile is such that the center of the stack could be located as close as 3.7 m from the edge of the barrier or as much as 8.5 m. The spacing was varied in the calculations.

The calculations indicated that a 1-meter-thick sand barrier located 5 m (center to center separation) from the TNT charge would obtain a velocity of 514 m/s (this value was obtained by averaging several computational stations in the wall). For the same conditions, a 0.5-m-thick sand barrier would obtain a velocity of 867 m/s, and a 2.0-m-thick barrier would obtain a velocity of 290 m/s. When the center to center spacing from the barrier was increased to 10 m, the velocity for the 1-m-thick barrier dropped to 443 m/s. Small amounts of venting in the barrier had only a small effect on the barrier velocity.

We chose to simulate the case of a 1-meter-thick barrier with a center to center separation between the barrier and the explosive stack of 10 m. It appeared that significantly thinner barriers could obtain velocities sufficient to cause prompt shock initiation of the acceptors, and thinner barriers might also have a problem in stopping all fragments. In retrospect, a thicker barrier may have been a better choice, as will be seen below.

## Description of the Test

To see the effect of such a barrier on the acceptor munitions, we designed an experiment which was intended to project a 1-meter-thick sand barrier at M107 projectiles at a velocity of about 400 m/s. The experimental arrangement is shown in Figures 1 and 2. A 380-mm-thick layer of ANFO (ammonium nitrate with 6 % fuel oil) explosive was sandwiched between two 1-m-thick layers of sand. The sand and explosive layers were 1.83 m high and 3 m wide. The detonation of the ANFO drove the sand barriers into two test chambers which were 2 m deep and had the same height and width as the sand barriers. One of the test chambers contained two pallets of Composition B-loaded M107 projectiles, and the other contained two pallets of instrumented, inert loaded M107s. The entire structure was buried below ground level at a test site at the New Mexico Institute of Technology.

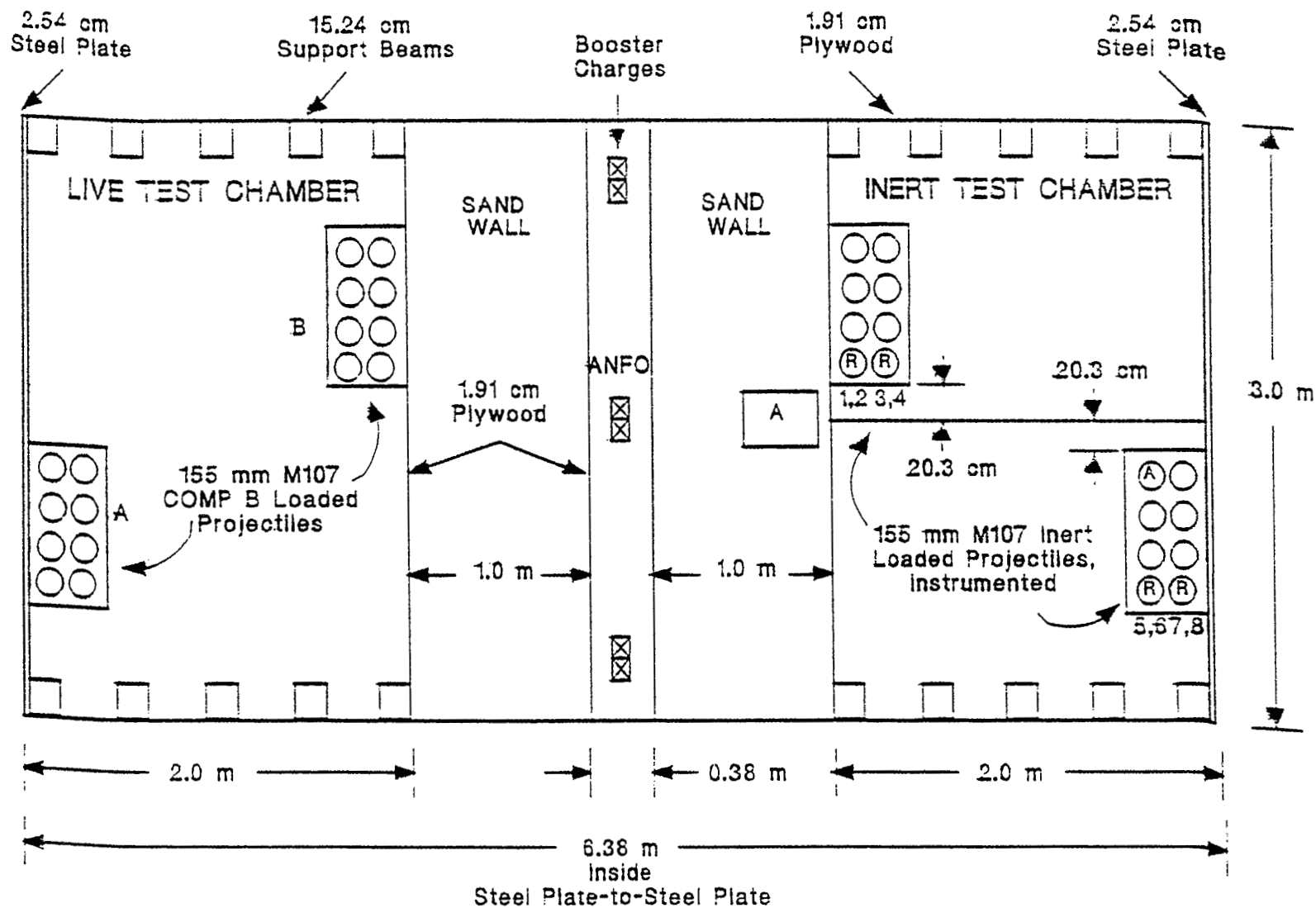


Figure 1. Top View of Experimental Setup.

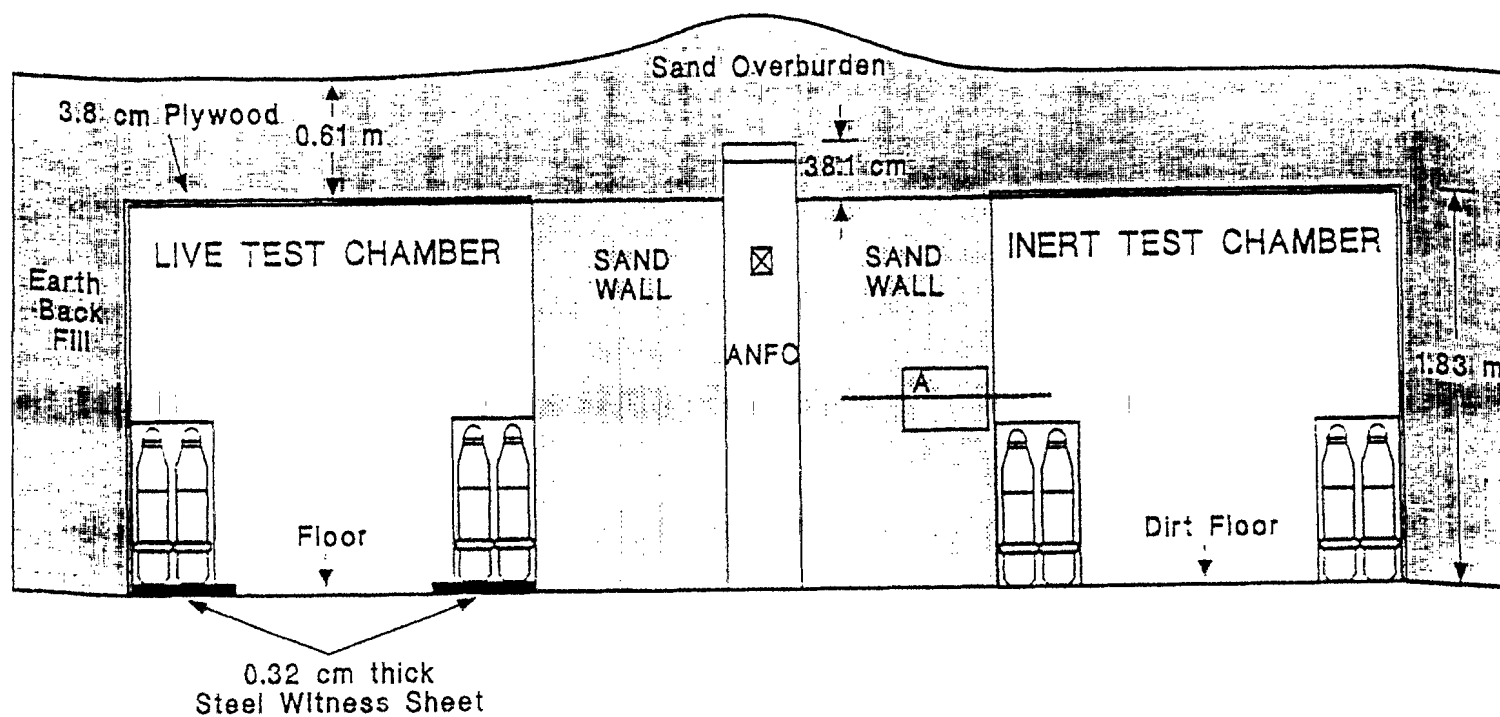


Figure 2. Side View of Experimental Setup.

A wooden structure was built to hold the explosive and the sand barriers and to keep earth from entering the test chambers. The sides of the sand barriers were constructed of two pieces of 9.5-mm plywood which were laminated together with wood glue to give a 19.1-mm-thick wood support. The opposite sides of the barrier were attached using multiple Kevlar straps to keep the walls from bowing as the sand was added. Figure 3 is a photograph of the structure that held the sand barriers and the explosive layer before the sand and explosive were loaded. Standard construction sand was used in the barriers and contained less than 5% rock. Any rocks which were present in the sand measured less than 12.7 mm in diameter. The sides of the test chambers were made of 19.1-mm-thick plywood supported by 152 × 152-mm wooden beams. The roof was a double thickness of 19.1-mm plywood, also supported by 152 × 152-mm wooden beams. Figure 4 shows one of the test chambers before it was buried. The rear wall of each test chamber was covered with a 25.4-mm-thick mild steel plate. The entire structure was buried in the ground, and the roof was covered with 610 mm of sand.

In the live-test chamber, one pallet of Composition B-loaded M107 projectiles was located immediately adjacent to the sand barrier and slightly off the center line as shown in Figure 1. The pallet was situated so that four rounds were against the sand barrier. The edge of the pallet was flush with the plywood retaining walls, which allows about 25 mm of free space between the plywood and the projectiles. Another pallet was located adjacent to the rear steel wall on the other side of the center line. A 3.2-mm steel witness plate was placed under each pallet, and the steel back wall of the test chamber also served as a witness plate.

The inert chamber was a mirror image of the live chamber, but the pallets contained inert rounds. Four of the acceptor rounds were instrumented with a total of eight carbon resistor gages<sup>5</sup>. The rounds that contained the resistor gages are marked with an "R" in Figure 1. One of the rounds was instrumented with a self-recording accelerometer<sup>6</sup> that was provided by personnel from the Waterways Experimental Station. It is marked with an "A" in Figure 1. A similar accelerometer was placed in the sand wall, centered on the face of the wall adjacent to the test chamber.

The ANFO was detonated using six 5-lb-charges of Thermex 200. The total weight of the ANFO was 2,268 kg.

## Simulations of the Test

Lawrence and Starkenberg (see their paper in this symposium) ran simulations of the test using the HULL code. As before, they used cylindrical symmetry to save computational time. The sand wall was represented by a cylinder 4 m in diameter and 1 m thick. The ANFO was also a 4-m-diameter cylinder initiated at a point on the center line. Since the diameter was somewhat greater than the actual lateral dimensions of the experiment, the computed barrier velocities are probably a little too high. The plywood forms which held the sand were not included in the calculations. The first simulations were solely for the purpose of determining the wall velocity as a function of the thickness of the ANFO. The calculations indicated that the first shock through the barrier accelerates the barrier to about two thirds of its final velocity, and the barrier continues to accelerate until it reaches the rear wall. With 400 mm of ANFO, the maximum velocity was 417 m/s (averaged over several stations 100 mm from the free surface of the barrier). With 300 mm of ANFO, the maximum velocity was 330 m/s. In the test, 380 mm of ANFO were used and interpolation of the computed results gives a predicted final velocity of about 400 m/s for the test condition. In the real test, the velocity was probably somewhat lower for reasons already stated. In another calculation of this type (not reported in the accompanying Lawrence and Starkenberg paper), we looked for evidence that the surface of the sand barrier might be "spalling" and moving off with a higher velocity than the rest of the wall. To see if this was so, the velocity was determined at a point 30 mm from the surface (instead of 100 mm). The result indicated that the surface was not moving

appreciably faster than the interior. The computed pressure in the sand supported this conclusion. It indicated that the shock pressure decreased markedly as the shock moved across the sand barrier, from about 64 kbar at the explosive-sand interface to about 7 kbar at the air-sand interface.

A second set of simulations was run to determine the pressure in the acceptors due to the impact of the sand. In this case, a 2-D plane-strain simulation was used, so the acceptor was represented as an infinitely long cylinder with constant wall thickness. One calculation simulated the impact of the sand on the rounds which were against the rear steel wall. In this case, the rounds are first shocked and then crushed by the impact. For this calculation, the wall was given a velocity of 360 m/s, and the calculation was started at the time the wall impacts the rounds. The maximum computed pressure in the rounds was 3.5 kbar, well below the pressures usually associated with shock initiation in undamaged composition B. A possibly significant feature of the calculations is that the pressure in the explosive in the acceptor round showed several strong oscillations with a period of about 18  $\mu$ s. Because of the complicated pressure-time history (see Lawrence and Starkenberg), the duration of the shock pressure cannot be determined in an unambiguous fashion. Near the front of the acceptor (but in the explosive), the pressure dropped almost to zero after about 18  $\mu$ s, but this was followed by further oscillations. At points closer to the interior of the acceptor, the oscillations were weaker, and it is more difficult to specify a shock duration.

Another simulation was run to determine the pressure in the acceptors that were near the sand wall. This calculation (not reported in the accompanying paper by Lawrence and Starkenberg) also used the plane-strain geometry, but it included the detonation of the explosive (along a line at the bottom of the ANFO) and the acceleration of the barrier. A 25-mm air gap was included between the edge of the wall and the acceptors, but the plywood was ignored. In this case, the impact of the sand produced a peak pressure in the acceptor of about 3.5 kbar, about the same as the pressure in the rounds against the rear wall. However, in this case, there was a second pressure pulse when the acceptor rounds hit the rear steel wall. The peak pressure for the second pulse was about 3.8 kbar, slightly higher than for the first pulse.

## TEST RESULTS

A crater measuring approximately 21.3 m  $\times$  10.7 m  $\times$  5.5 m deep was created. The rear steel walls of the test chambers were destroyed, and only portions of the bottom section were recovered. No other portion of the test chamber was recovered. Several of the inert instrumented projectiles were recovered. These were severely cracked, and several were broken into multiple pieces. The bottom rear steel wall recovered in the inert chamber was severely deformed, but contained no perforations. Figures 5, 6, and 7 show the recovered portion of the rear wall from the inert chamber, and inert projectiles recovered after the test. Note the severe damage the projectiles experienced. None of the recovered projectiles have the nose plug in place, and all are badly dented or split open. The inert fill is seen to be extruded from the nose opening.

There was substantial evidence that the live acceptors detonated. Minimal projectile fragments were recovered: one base fragment and portions of side fragments. The steel witness sheets located under the live projectile pallets were severely deformed and torn into multiple pieces. No live acceptor projectiles were recovered intact. There were also multiple fragment perforations in the rear steel wall adjacent to the live acceptor pallet (but the steel wall on the inert side was not perforated). These perforations appear to have been made by a round which detonated at some distance from the wall. Thus, it appears that the rounds near the sand wall may have detonated, and they probably detonated before they impacted the rear wall.

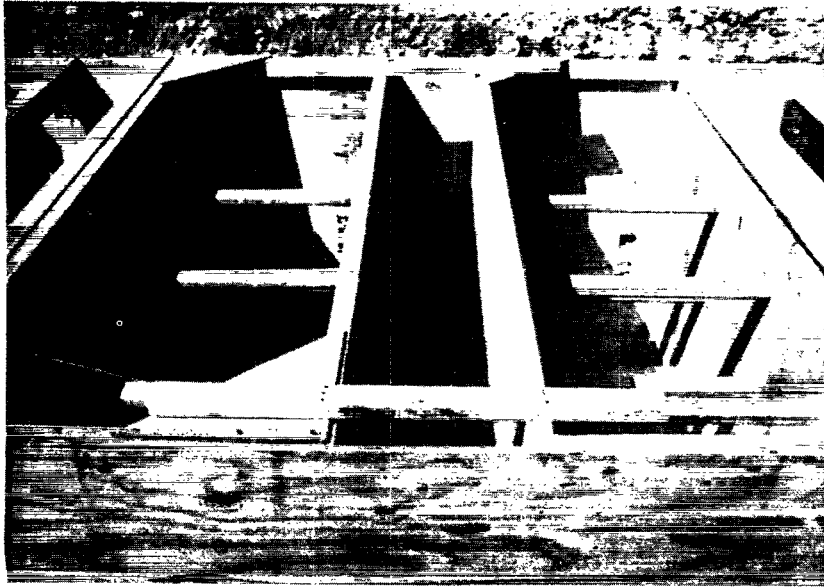


Figure 3. Photograph of the Structure Holding the Sand Barrier and the Explosive.

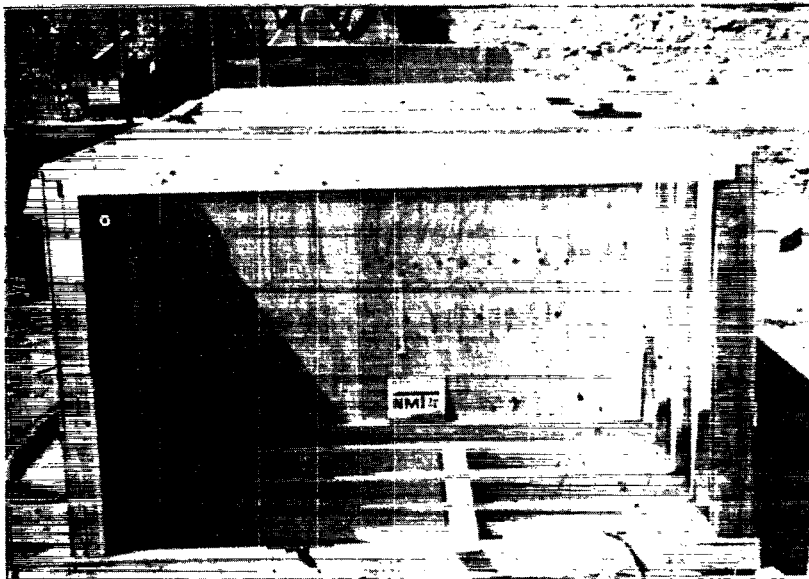


Figure 4. Photograph of the Structure Surrounding the Test Chambers.

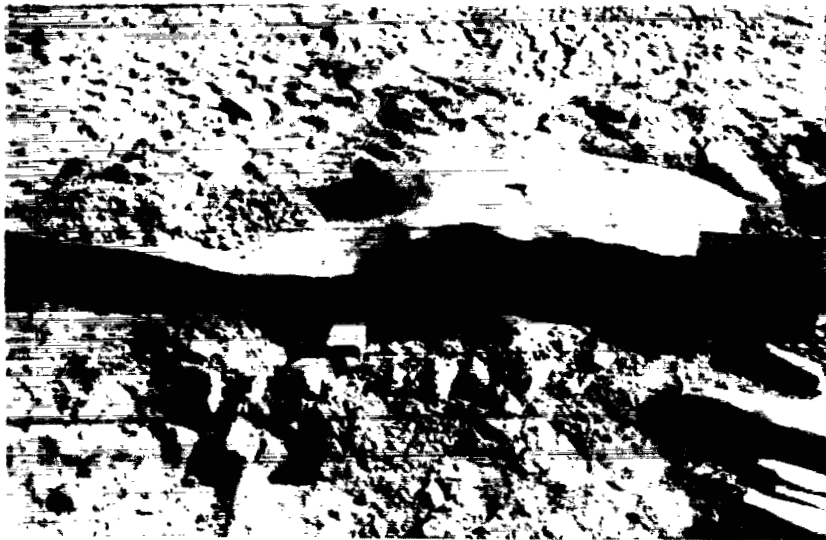


Figure 5. After Test Photograph of a Portion of the Steel Wall on the Inert Side.

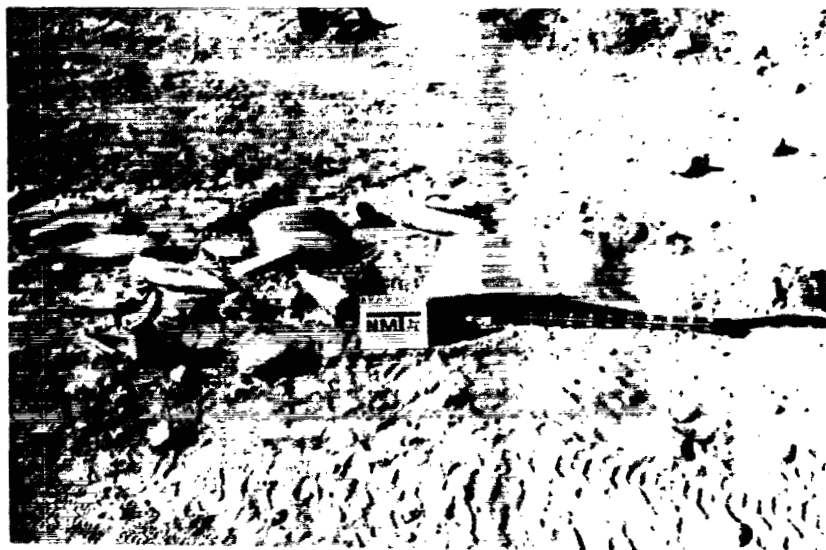


Figure 6. After Test Photograph of the Inert Rounds.

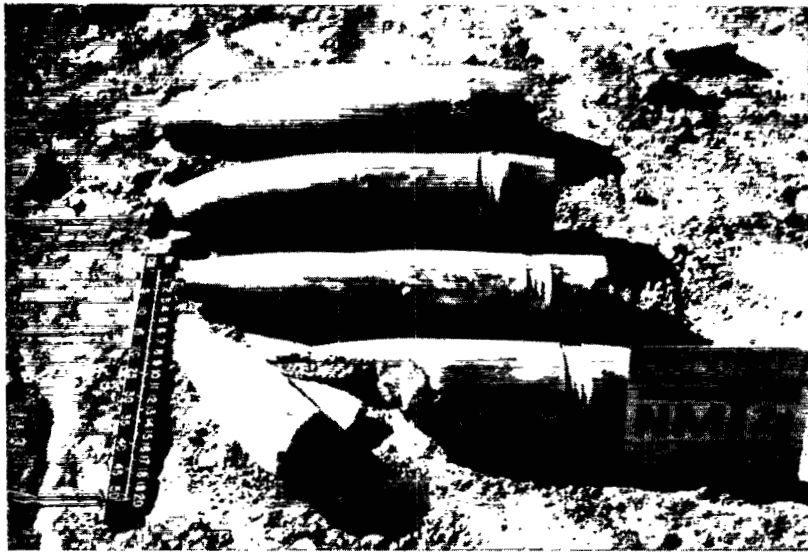


Figure 7. After Test Photograph of the Inert Rounds.

We believe all of the rounds detonated, but there is some question about this because some large fragments from the live projectiles were found. However, it is known that large fragments can be produced when multiple rounds in close proximity detonate<sup>6</sup>. Our conclusion that all rounds detonated is based on the absence of any base fragments and the damage to the witness plate that was under the rounds. Figures 8, 9, and 10 show the recovered portion of the rear wall from the live chamber, some of the larger fragments from the live projectiles after the test, and the steel witness plate that was under the live projectiles.

The accelerometer in the sand wall was not recovered. The one in the inert pallet was recovered, but it had been destroyed by the event, and it was not possible to extract any data. Records were obtained from six of the eight resistance gages. However, after analysis, we have concluded that the records were not meaningful. It appears that the gage leads broke early in the event and the apparent signal observed later was caused by shorting of the leads.

## Discussion

The detonation of the acceptor rounds was somewhat of a surprise. The predicted shock pressure in the rounds was less than 4 kbar, well below the pressures usually associated with initiation of detonation in composition B. In fact, in aquarium tests, Liddiard<sup>7</sup> found that 4 kbar was the threshold point for detecting shock-induced burning (not detonation) in Composition B. One might also analyze these results in terms of the "critical energy" criterion<sup>8</sup> for initiation. We are very dubious about the applicability of this criterion to the present circumstance, but we considered it anyhow. Reference 8 gives the critical energy of Composition B as  $1,850 \text{ kJ/m}^2$ . If we take the pulse duration as  $18 \mu\text{s}$ , a pressure of 7.0 kbar is required for initiation of detonation. However, if the pulse duration were taken as  $100 \mu\text{s}$ , which might



Figure 8. After Test Photograph of a Portion of the Steel Wall on the Live Side.



Figure 9. After Test Photograph of the Larger Fragments from the Live Rounds.

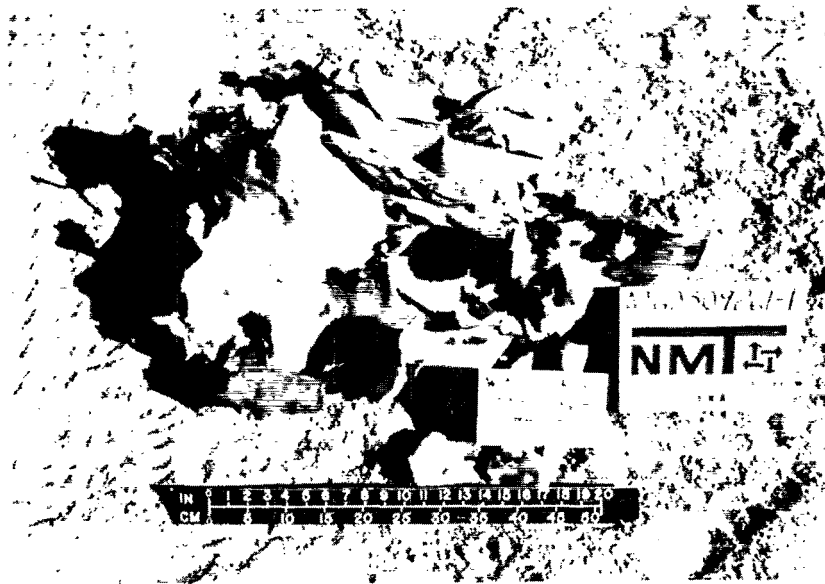


Figure 10. After Test Photograph of the Witness Plate Under the Live Rounds.

be justified on the basis of the Lawrence and Starkenberg calculations, the critical pressure would be 3.0 kbar. This is in the range of the computed maximum pressures, but it is higher than the average pressure over 100  $\mu$ s (see Lawrence and Starkenberg).

We can only speculate on why detonation occurred. A prime suspect in our minds is the fact that the acceptors saw multiple pressure pulses. This was true in two respects. First, there were strong oscillations associated with the impact of the sand wall on the rounds. Second, for the rounds adjacent to the sand wall, there was a second shock when they hit the rear wall. As has often been discussed in the explosives literature, an earlier event can damage the explosive and sensitize it to a later event. If the rounds detonated while they were still some distance from the rear wall, as the evidence appears to indicate, the second effect is ruled out, but the first is a strong possibility.

Another possible source of initiation to violent reaction of the live projectiles is the crushing that occurred as evidenced by the recovered inert projectiles. Although this is a known mechanism, the critical parameters governing this mechanism are not yet well understood, particularly for heavily cased explosives. This may not be the mechanism that produced the fragments that perforated the rear wall, but there may well have been different mechanisms for different projectiles depending on their location.

The significant result of this study is that, in situations such as this, detonation may occur with stimuli much weaker than one might expect based on small scale data. In the present case, it appears that a shock of 3.5 kbar was sufficient to cause detonation (although several oscillations may have been involved).

## REFERENCES

- <sup>1</sup>Frey, R., J. Watson, G. Gibbons, and D. Collis. "Some Results Concerning the Mechanism of Sympathetic Detonation." Proceedings of the JANNAF Propulsion Systems Hazards Meeting, February 1989.
- <sup>2</sup>Lewis, M. J., G. J. Friesenhahn, and P. T. Nash. "Mark 84 Buffered Storage Test Series." Ogden Air Logistics Center Report MNW-TR-87-50102AC, 1988.
- <sup>3</sup>Collis, D. L. "Fragment Penetration Studies: Sand Test Data." New Mexico Institute of Mining and Technology, TERA Group Report NMT/TERA No. T-84-1540-U, 1984.
- <sup>4</sup>Ramsey, R., J. Powell, and W. Smith. "Fragment Hazard Investigation Program." Minutes of the 18th Explosives Safety Seminar, 1978.
- <sup>5</sup>Ginsberg, M., and B. Asay. "Commercial Carbon Composition Resistors as Dynamic Stress Gauges in Difficult Environments." Review of Scientific Instruments, Vol. 62, No. 9, 1991.
- <sup>6</sup>Feinstein, D. I., and H. H. Nagaoka. "Fragment Hazards from Munitions Stacks." Twelfth DDESB Explosive Safety Seminar.
- <sup>7</sup>Liddiard, T. "The Initiation of Burning in High Explosives by Shock Waves." Fourth Symposium (International) on Detonation, Office of Naval Research Publication ACR-126.
- <sup>8</sup>Dobratz, B. M., and P. C. Crawford. "LLNL Explosives Handbook." UCRL-52997, Change 2, 1985.